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QUANTITATIVE GEOMORPHIC ANALYSIS TO EVALUATE FLOOD HAZARDS

ABSTRACT: DELLA SETA M., DEL MONTE M. & PASCOLI A., *Quantitative geomorphic analysis to evaluate flood hazards*. (IT ISSN 1724-4757, 2005).

The aim of this study is to evaluate flood hazards through the use of quantitative geomorphic methods, which were already applied to estimate mass movement hazards and accelerated erosion hazards in some Italian areas. The study area is the Fiume Ombrone drainage basin (Central Italy), where wide zones of the main valley floors have been recently flooded. In the last decade of the past century the frequency of these hazardous events has increased.

Firstly, historical data and geomorphological survey provided maps of flooded areas. Successively, a map overlay was performed between these maps and each thematic map representing the main factors of flood hazard (topography, surface drainage, climate, land use) expressed by suitable parameters. Map overlay allowed to weight the influence of each category of factors on the occurrence of flood events. To evaluate the effects produced by the simultaneous influence of different factors, the thematic maps of these factors were overlaid, in turn, on each map of flooded areas and the attributes of the different factor types were combined. Results obtained allowed the identification of zones prone to flood hazard and the evaluation of their hazard index.

After this method, different maps of flood hazards were obtained, which show the spatial variation of the hazard index for flood events with different recurrence intervals.

KEY WORDS: Quantitative geomorphology, Flood hazards, Drainage basins, Central Italy.

RIASSUNTO: DELLA SETA M., DEL MONTE M. & PASCOLI A., *Metodi di analisi geomorfica quantitativa per la valutazione della pericolosità per inondazione fluviale*. (IT ISSN 1724-4757, 2005).

Lo scopo di questo lavoro è di valutare la pericolosità per inondazione fluviale attraverso l'utilizzo di metodi di geomorfologia quantitativa, già applicati in precedenza per la stima della pericolosità per movimenti in massa e per erosione accelerata in alcune aree italiane. È stato preso in esame il bacino idrografico del Fiume Ombrone (Toscana, Italia centrale), all'interno del quale ampie zone di fondovalle sono state colpite recentemente da fenomeni di esondazione, la cui frequenza è aumentata negli ultimi anni.

Il reperimento di dati storici di portata e di informazioni relative alle aree inondate dai singoli eventi alluvionali, integrate dal rilevamento geomorfologico, hanno permesso di elaborare carte relative alla distribuzione delle aree inondate. Successivamente ciascuna di queste carte è stata sovrapposta a ognuna delle carte tematiche relative ai principali fattori predisponenti i fenomeni di inondazione fluviale (fattori morfologici, idrografici, climatici e antropici), espressi in forma parametrica. Dalle carte di sintesi così ottenute sono stati scelti i più significativi fattori predisponenti relativi al manifestarsi degli eventi studiati. La sovrapposizione cartografica ha permesso anche di pesare l'influenza di ogni fattore selezionato sul manifestarsi del fenomeno studiato. A questo punto, per valutare la predisposizione indotta dalla presenza simultanea di più fattori, le carte tematiche dei fattori predisponenti selezionati sono state sovrapposte contemporaneamente e gli attributi dei differenti fattori sono stati combinati. I risultati ottenuti hanno consentito di identificare le zone maggiormente predisposte a subire inondazioni fluviali e di valutarne l'indice di pericolosità.

Applicando il metodo descritto sono state ottenute diverse carte della pericolosità per inondazione fluviale, in ciascuna delle quali è evidenziata, dato un certo tempo di ritorno, la variazione spaziale del relativo indice di pericolosità nella piana di Grosseto.

TERMINI CHIAVE: Geomorfologia quantitativa, Pericolosità per inondazione fluviale, Bacini idrografici, Toscana, Italia.

INTRODUCTION

Many recent works focused on «geomorphological hazards», with the twofold aim of identifying areas in which geomorphological hazardous events are likely to occur, and developing appropriate methods for risk re-

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duction (Brunsden & Prior, 1984;Varnes & *alii*, 1984; De Graff & Canuti, 1988; Einstein, 1988; Embleton & *alii*, 1989; Panizza & Piacente, 1993; Reading, 1993; Fell, 1994; Allison, 1996; Maerker & *alii*, 2001; Del Monte & *alii*, 2002; Chester, 2002; Panizza, 2002).

As known, many preconditions of hazardous events can be expressed parametrically through quantitative geomorphic analysis. This quantitative approach has been already and successfully applied to evaluate the geomorphological hazards in some Italian drainage basins deeply affected by hazardous processes, mainly due to gravity and sheet, rill and gully erosion (Del Monte & *alii*, 2002). In this work the same approach is applied to quantify flood hazard.

STUDY AREA

The drainage basin of Fiume Ombrone (Central Italy; fig. 1) has been chosen as case study, because of its propensity to marked and fast morphological changes and particularly to floods causing severe damages, as registered during the past century.

In the study area the mean annual rainfall ranges from 1550 mm to 550 mm (Barazzuoli & Salleolini, 1993). Mean monthly values range from 220 mm in November to 10 mm in July. Rainfalls of consecutive days are frequent, sometimes exceeding 250 mm in 5 days. The mean annual temperature is 13.4 °C; the maximum of the mean monthly values is registered in July (23 °C) and the minimum in January (5 °C).

FIG. 1 - Location of the study area.

The Ombrone drainage basin is located in an Early Pliocene tectonic depression; it is part of a horst-and-graben system, tied to the extensional tectonic phase (following the Miocene compressive one) responsible for the emplacement of the Apennine structures (Lazzarotto, 1993).

Marine clays, sands and conglomerates of the neo-autochthonous complex (Pliocene) filled up the structural lows, while structural highs are made up of Allochthonous mainly clayey and marly flysch (Lower Cretaceous-Paleocene) and autochthonous carbonate rocks (Triassic-Eocene).

In the south-eastern sector of the basin volcanic products of the Monte Amiata and Radicofani complexes (Pleistocene) crop out. Terraced and present alluvial deposits are present on the valley floors of Fiume Ombrone and its tributaries (Bravetti & Pranzini, 1987).

The main morphological effects of destabilising slope processes were surveyed through air photo interpretation and geomorphological multi-years field survey. Although they differ in intensity and distribution, the potentially hazardous processes are mainly due to gravity and surface running waters. Badlands are widespread in the north-eastern sector, where pliocenic clays crop out. Parallel slope retreat and frequent mass movements affect the slopes. Caprock is a key factor in badland evolution as it allows the preservation of these landforms on steep slopes. After the caprock removal, however, badlands evolve faster; as a consequence, slope gradients decrease and erosion rate slows down. Rounded-edged badlands (locally called «biancane») are typical landforms on the low-gradient slopes on Pliocene argillaceous outcrops. Some of them seem to result from the evolution of previous knife-edged badlands.

Gravity-driven processes are found in large areas within the drainage basin. Slumps occur on the clay and flysch outcrops, particularly were slope gradients are high. Creep is usually present on the low-gradient slopes of the clayey outcrops. In places, creep is changed into mudflows that sometimes have damaged buildings of artistic interest.

Human activity is an important factor of landscape evolution, as it often modified both erosion and depositional landforms.

From the historical point of view, the Fiume Ombrone alluvial and coastal plain is a recent conquest of the human being that in the past centuries had always kept away from the marshy and malaric «low lands». A hard, long lasting work for water regime setting (fig. 2) allowed originally depopulated regions to become privileged sites for peopling and for intensive agriculture practice.

This region underwent several floods in the last century; specifically, during the flood event in 1966 (fig. 3) more than 300 km^2 of the Grosseto plain were inundated.

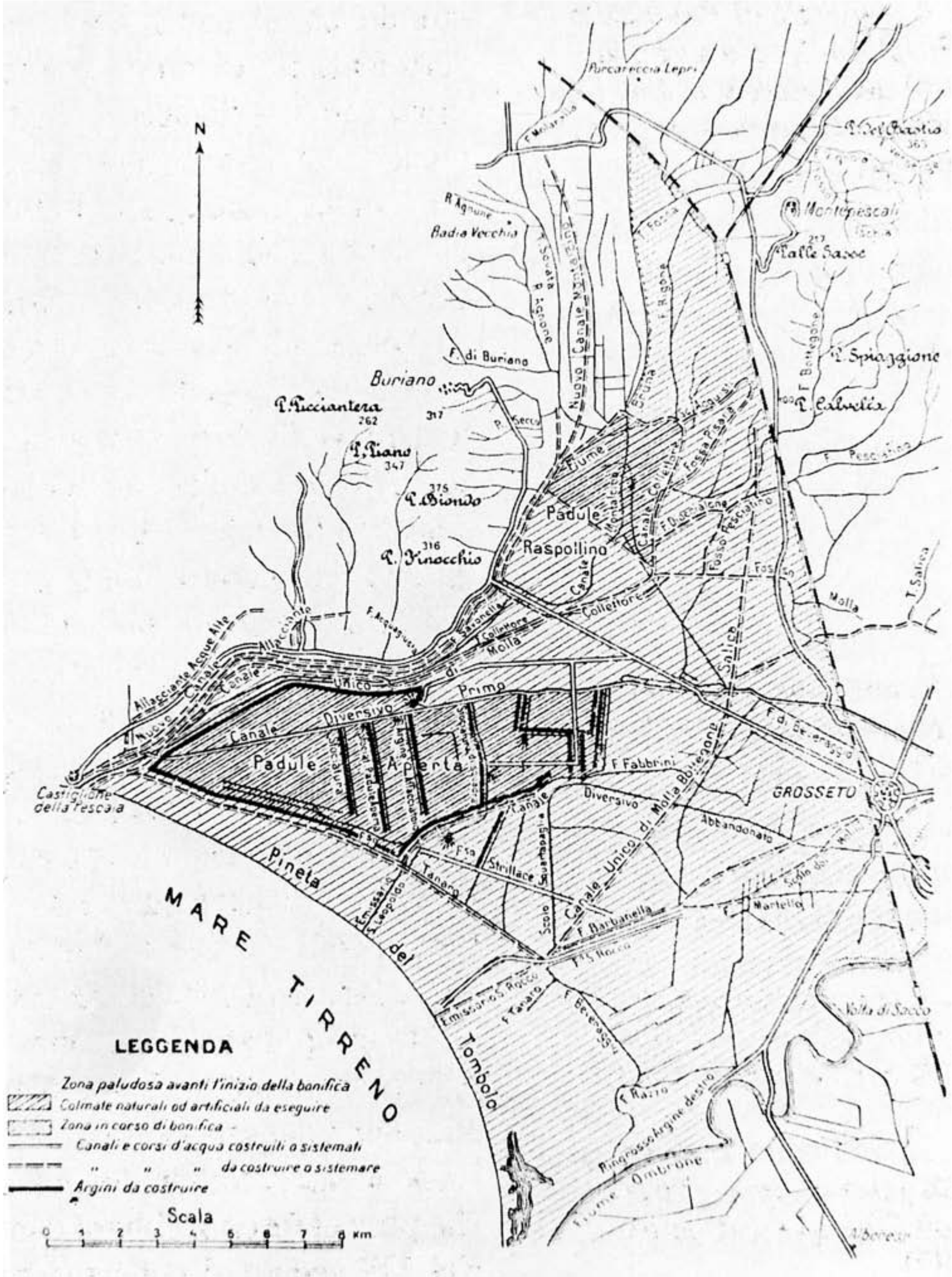

FIG. 2 - Historical map showing the 1930 water regime setting project. Striped fill indicates areas with water regime setting in progress at 1930, double stripe marks areas to be naturally or artificially filled up and bold lines indicates banks to be built (after Rombai & Signorini, 1993).

EVALUATION OF FLOOD HAZARD

The methodology performed to evaluate flood hazard is shown in the flow-diagram of fig. 4.

Firstly, the main features that may contribute to the occurrence of potentially floods were examined and translated into morphometric parameters (fig. 4a). The differences in elevation per unit areas - expressed by the *amplitude of relief* (A) - were calculated. Moreover, drainage network extent and degree of organization were quantified through *drainage density* (*D*: Horton, 1945) and through some *hierarchical parameters* (*Rb*: Horton, 1945; Δa and *ga*: Avena & *alii,* 1967). Finally, the *sinuosity index* (S), the *minimum distance from main stream* (F) and the *slope gradient* (G) values of the main floor valleys were computed.

The above parameters were calculated for sub-basins or for unit of areas, depending on their intrinsic significance. Thus, the distribution of their values throughout the study areas was plotted on coropleth maps (fig. 4b).

Historical data about floods occurred in the past century were examined (fig. 4c), with special focus on the

FIG. 3 - Flood effects in Grosseto (4th November 1966; after Barazzuoli & Salleolini, 1993).

events following the 1966 large one. In fact, since this event, records about the areas affected by each flood event, corresponding to a specific discharge, in some cases have been mapped, or it was possible to infer their perimeters basing on suitable historical reports. A map of the areas inundated was obtained for each flood event occurred since the 1966 (fig. 4d). To estimate the recurrence intervals (*Tr*), the method proposed by Gumbel (1958) was used (fig. 4d). The Fiume Ombrone discharge data (Q) were collected at the Sasso d'Ombrone station (tab. 1); they are relative to the 1926-1994 time span (with some interruptions). After the Gumbel distribution, the probability ($\Phi(x)$) of non-overcoming the discharge value is related to the reduced variable of the same distribution by:

$$y = -\ln[-\ln\Phi(x)] = -\ln(1\text{-}1/Tr)$$

where x is the discharge value with recurrence interval Tr, and $\Phi(x) = (1\text{-}1/Tr)$ expresses the probability of non-overflowing. Table 1 shows Gumbel's function values.

In order to identify the most important factors of flood hazards, the flood maps were overlain, in turn, on each of the thematic maps showing the areal variations of the morphometric parameters (fig. 4e). By evaluating the spatial join between flooded areas and the attribute classes distribution shown in each thematic map, the most significant factors of the flooded areas were pointed out for each event. It must be stressed that the more the flooded areas correspond to a small range of a selected factor values (ideally to a single class), the more that factor is significant. This comparative analysis of cause/effect relationships led to the selection of four morphological parameters – expressed by *amplitude of relief* (A), *slope gradient* (G), *sinuosity index* (S), *minimum distance from main stream* (F) – whose distribution provides the best explanation of the flood occurrence in the study area (fig. 4f). The less significant factors were discarded.

Map overlay also allowed the weight of each class of the factors to be determined. After having measured the cumulative intersection between the flooded areas and the areas occupied by a given class of a factor, the weight is obtained by normalizing the intersection area to the cumulative area occupied by that class. Then, the thematic maps of the selected factors were overlain and the attributes of the different categories were combined (fig. 4g). In this way I areas were obtained (1) and the equation was derived (2) to compile the maps of flood hazard (fig. 4h).

The I areas represent all the possible intersections among the different categories of the factors of flood occurrence:

$$(1) \qquad a_i = a_{j,k,l,m} = \left[\left(A_j \bigcap_{j=1}^{J}\bigcap_{k=1}^{K} G_k\right)\bigcap_{l=1}^{L} S_l\right]\bigcap_{m=1}^{M} F_m$$

where $I = JKLM$ = n. of max possible areas.

TABLE 1 - Discharge (Q) data (1926-1994) and Gumbel's function values for the Fiume Ombrone, where y = f[Φ (Q)], Φ = probability of non-overflowing, *Tr* = recurrence interval.

a (year)	**Maximum Discharge (m^3/sec)**	**y**	**Φ(x)**	**Tr**
1994	132	-0,551	0,177	1,215
1933	198,9	-0,422	0,218	1,278
1931	204,8	-0,411	0,221	1,283
1972	259,7	-0,306	0,257	1,346
1971	262,1	-0,301	0,26	1,351
1952	269,1	-0,288	0,263	1,356
1967	272,3	-0,282	0,266	1,362
1932	286,7	-0,254	0,275	1,379
1955	289,6	-0,248	0,278	1,385
1973	312,4	-0,205	0,293	1,414
1970	319,4	-0,191	0,298	1,424
1993	336,9	-0,158	0,31	1,449
1980	348,7	-0,135	0,32	1,47
1954	367,4	-0,099	0,33	1,492
1977	367,4	-0,099	0,33	1,492
1974	395,5	-0,0456	0,35	1,538
1976	414,8	-0,0086	0,365	1,575
1956	416,5	-0,0053	0,366	1,577
1969	431,7	0,024	0,377	1,605
1962	435,2	0,035	0,38	1,613
1960	441,1	0,042	0,383	1,62
1951	456,3	0,071	0,394	1,65
1975	464,5	0,087	0,399	1,664
1961	486,7	0,129	0,415	1,709
1958	523,1	0,199	0,441	1,789
1953	528,8	0,21	0,445	1,801
1957	538,2	0,228	0,451	1,821
1959	551,1	0,253	0,46	1,852
1981	559,5	0,269	0,466	1,873
1979	572,6	0,294	0,475	1,905
1982	604,9	0,356	0,496	1,984
1934	608,4	0,362	0,498	1,992
1968	625,9	0,396	0,51	2,041
1963	627,1	0,398	0,511	2,045
1978	657,5	0,457	0,531	2,132
1992	772,2	0,676	0,601	2,506
1929	781,6	0,694	0,607	2,544
1964	787,4	0,706	0,61	2,564
1930	966,4	1,05	0,705	3,39
1928	1003,9	1,12	0,722	3,598
1927	1116,2	1,336	0,7688	4,325
1937	1117,4	1,338	0,769	4,329
1936	1133,7	1,37	0,776	4,464
1935	1193,4	1,48	0,796	4,902
1926	1357,2	1,798	0,847	6,536
1965	1485,9	2,044	0,878	8,197
1940	2786,6	4,54	0,989	90,909
1966	3110,1	5,16	0,9943	175,44
1944	3120,1	5,18	0,9944	178,57

Then the following product was computed, which depends upon the probability of flood occurrence in each of the *I* areas:

$$(2) \qquad P(a_i) = (Af_j / A_j) \cdot (Af_k / G_k) \cdot (Af_l / S_l) \cdot (Af_m / F_m)$$

where:

$P(a_i)$ = hazard index for flood occurrence in the area a_i
Af_j, Af_k,... = area affected by flood in the classes *j, k,...*
A_j = area covered by amplitude of relief *j*
G_k = area covered by slope gradient *k*
S_l = area covered by sinuosity index *l*
F_m = area covered by distance from main stream *m*
(obviously, *P* values range between 0 and 1).

RESULTS

The proposed method allows to create flood hazard maps indicating the general distribution of flood probability (P) values for each flooding event with a given recurrence interval *Tr*. Figure 5 shows an example of zonation maps, based on the distribution of different values of flood probability (P) within the Grosseto plain (lower Ombrone valley), for flow *Tr* = 2.5 years and *Tr* = 180 years.

In the first case (*Tr* = 2.5 years, fig. 5a) just small areas in the proximity of the main river are likely to undergo flood events with a probability higher then 5%. All the main towns show P values lower than 0.5%, a part from some outlying zones to the South of Grosseto town and some isolated buildings, which fall within a P class between 0.5% and 5%. The most of Grosseto town has probability lower than 1‰ to undergo flood events with *Tr* = 2.5 years.

On the other hand, considering a case with flood intensity comparable to those of the 1966 event and *Tr* = 180 years (fig. 5b), it comes out that a small portion of the south-eastern Grosseto town, along with some isolated buildings located in the Ombrone alluvial plain, have flood probability ≥ 30%. Some minor towns and the centre of Grosseto fall in a class with P values ranging between 5% and 30%, while just very far from the main river and in areas with higher amplitude of relief, P values are lower than 3%.

DISCUSSION AND CONCLUSIONS

The comparative analysis of the morphological factors and effects of flooding led to the identification of areas more or less prone to flood hazard.

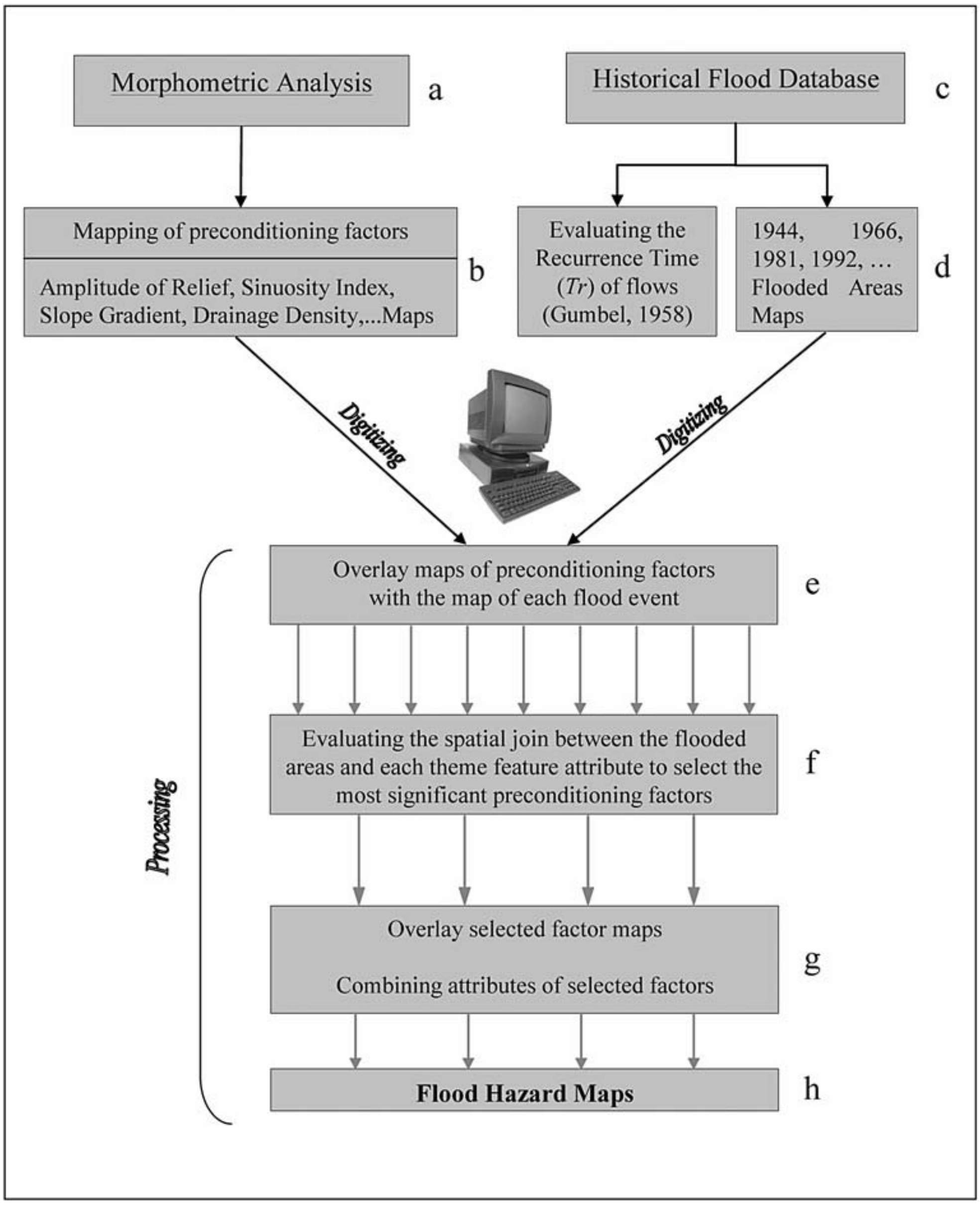

FIG. 4 - Flow diagram showing the performed methodology.

Nevertheless, there are several intrinsic limits which restrict the results obtained. They are due to incomplete cartographical data and to fragmented hydrographical records in the past. Moreover, the reliability of discharge evaluation may be uncertain, if modifications occur in the main stream channel, such as in the entire drainage network, due to natural and human factors.

Thus, the complex problem of evaluating flood hazard needs further and more detailed studies to achieving an unbiased estimation of flood occurrence capable of producing extensive damage. Results obtained show that quantitative geomorphic analysis provides a simple – although partial – contribution to this aim, open to any improvement.

Concluding, as the Fiume Ombrone case has shown, the proposed method proved useful to provide flood hazard maps based on morphological and hydrological quantitative data; essential requirement is that a detailed cartography of the flooded areas for at least 20 of the main flood events of the last 40-50 years is available or derivable by the use of GIS technology.

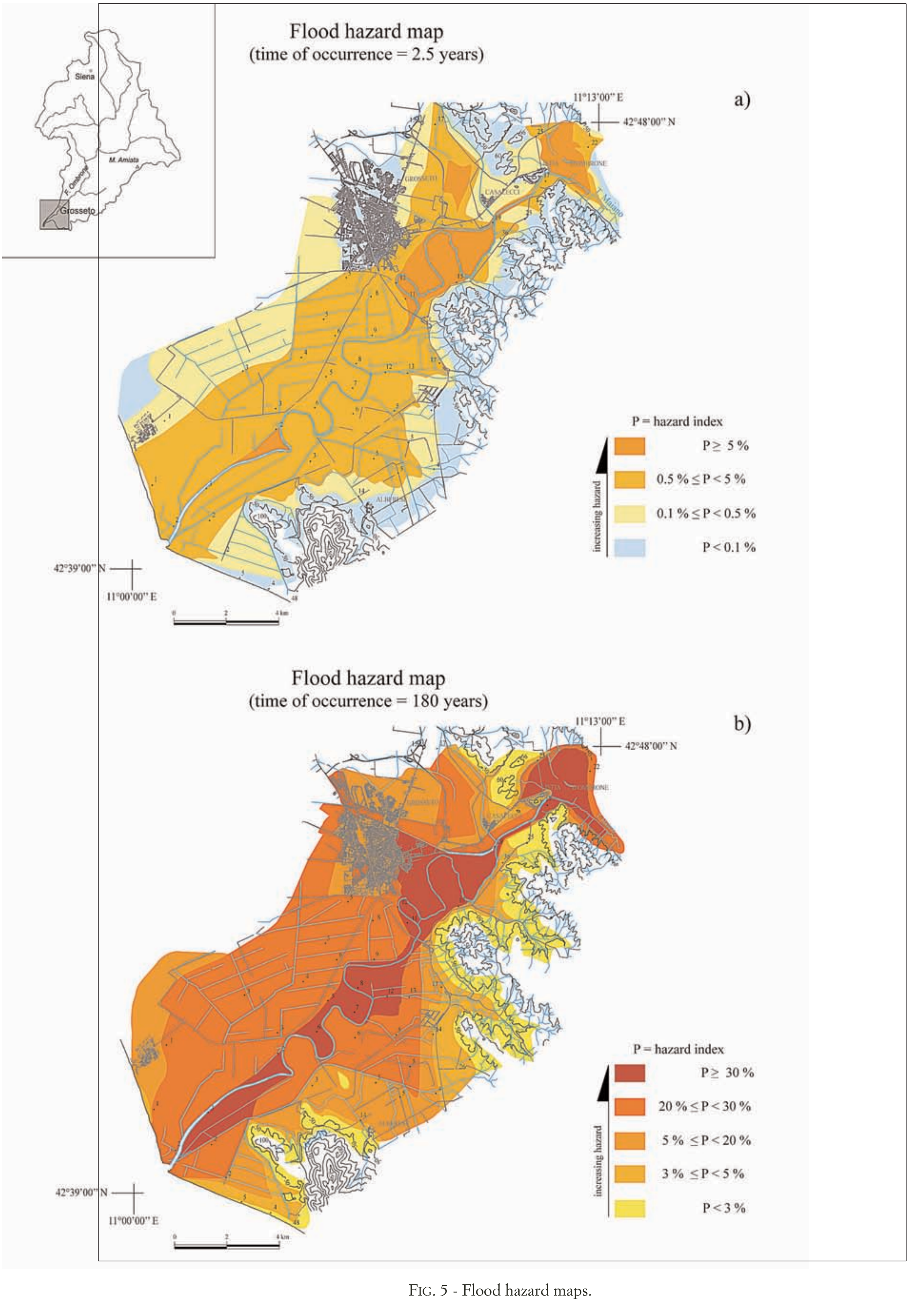

FIG. 5 - Flood hazard maps.

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